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**National Aeronautics and
Space Administration**

**NASA-STD-P023
AUGUST 17, 2001**

ELECTRICAL BONDING FOR NASA LAUNCH VEHICLES, SPACECRAFT, PAYLOADS, AND FLIGHT EQUIPMENT

NASA TECHNICAL STANDARD

FOREWORD

This standard is approved for use by NASA Headquarters and all NASA Centers and is intended to provide a common framework for consistent practices across NASA programs.

MIL-B-5087B, Bonding, Electrical, and Lightning Protection, For Aerospace Systems had been the basic bonding standard for years before its cancellation by the military. MIL-STD-464, Interface Standard for Systems Electromagnetic Environmental Effects Requirements, superseded MIL-B-5087B for military projects. Electrical bonding requirements make up only a small section of MIL-STD-464, and MIL-STD-464 is not applicable for NASA projects. The intent of this NASA standard is to provide stand-alone requirements and to provide enough data to help modify requirements or to allow waivers if needed.

Requests for information, corrections, or additions to this standard should be directed to the Electromagnetic Environmental Effects Team, ED44, MSFC, AL 35812. Requests for general information concerning NASA Technical Standards should be sent to the NASA Technical Program Standards Office, ED41 MSFC, AL 35812, (telephone 205-544-2448). This and other NASA standards may be viewed and downloaded, free-of-charge, from our NASA Standards Homepage: http://standards.nasa.gov.

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Chief Engineer

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ELECTRICAL BONDING FOR NASA LAUNCH VEHICLES, SPACECRAFT, PAYLOADS, AND FLIGHT EQUIPMENT

1. SCOPE

1.1 Scope. This standard defines the basic electrical bonding requirements for NASA launch vehicles, spacecraft, payloads, and equipment.

1.2 Purpose. The intent of this standard is to provide fundamental aerospace electrical bonding requirements. This standard classifies electrical bonds according to their purpose and states the requirements for the various classes. The rationale for specific requirements is stated where possible. Additional data is provided to support tailoring for new applications if necessary.

1.3 Applicability. This Standard recommends engineering practices for NASA programs and projects. It may be cited in contracts and program documents as a technical requirement or as a reference for guidance. Determining the suitability of this Standard and its provisions is the responsibility of program/project management and the performing organization. Individual Provisions of this standard may be tailored (i.e. modified or deleted) by contract or program specifications to meet specific program/project needs and constraints.

1.4 Order of Precedence. Where this document is adopted or imposed by contract on a program or project, the technical requirements of this document take precedence, in the case of conflict, over the technical requirements cited in other referenced documents.

Program specific standards are already in effect for the space shuttle, as defined in NSTS 37330, and for the space station, as defined in SSP 30245.

2. DOCUMENTS

2.1 Applicable Documents. The documents in this paragraph are applicable to the extent specified herein.

MIL-C-5541E	Military Specification, Chemical Conversion Coatings on Aluminum and Aluminum Alloys
MIL-C-81706	Military Specification, Chemical Conversion Materials for Coating Aluminum and Aluminum Alloys
MIL-M-3171C	Military Specification, Magnesium Alloy, Processes for Pretreatment and Prevention of Corrosion on

2.2 Referenced Documents. The documents in this paragraph are for reference only.

AFSC DH 1-4	Air Force Systems Command, Design Handbook, Electromagnetic Compatibility
MIL-B-5087B	Military Specification, Bonding, Electrical, and Lightning Protection, for Aerospace Systems

MIL-STD-464	Department of Defense Interface Standard, Electromagnetic Environmental Effects, Requirements for Systems
MIL-STD-889B	Military Standard, Dissimilar Metals
NSTS 37330	Bonding, Electrical, and Lightning Specifications
SAE ARP 1870	Aerospace Systems Electrical Bonding and Grounding for Electromagnetic Compatibility and Safety
SAE ARP 5412	Aircraft Lightning Environment and Related Test Waveforms
SSP 30245E	Space Station Electrical Bonding Requirements
STP 6511J	Lockheed Martin, Electrical and Electronic Bonding Connections
Radio Engineers' Handbook	F. E. Terman, McGraw-Hill Book Co., Inc., New York and London, 1943
Lightning Protection of Aircraft,	Fisher, Plumer, and Perala, LTI, Inc., Pittsfield, MA, 1990

3. ACRONYMS

3.1 ACRONYMS used in this Handbook are:

λ	Wavelength
μH	Microhenries
A	Area
ac	Alternating current
AWG	American Wire Gauge
C	Capacitance
CLASS "C"	Class of bond for intentional current return
CLASS "H"	Class of bond for fault current return
CLASS "L"	Class of bond for lightning current
CLASS "R"	Class of bond for radio frequency current
CLASS "S"	Class of bond for dissipation of electrostatic charge
cm	Centimeters
d	Distance, diameter
dB	Decibels
dc	Direct current
E_I	Initial charge voltage
E_s	Chosen or final "safe" voltage

EED	Electro-explosive device
ESD	Electrostatic discharge
f	Frequency
f_{res}	Resonant frequency
GFRP	Graphite filament reinforced plastic
Hz	Hertz
I_{max}	Maximum current
J	Joules
k	Dielectric constant
kHz	Kilohertz
kV	Kilovolts
L	Inductance
l	Length
ln	Natural logarithm = 2.303 x $\log_{10}$
mA	Milliamps
MHz	Megahertz
mJ	Millijoules
NASA	National Aeronautics and Space Administration
pF	Picofarads
Q	The ratio of reactance to resistance in a tuned circuit
R	Resistance
r	Radius
RF	Radio frequency
R_t	Total resistance
t	Thickness
T	Time of discharge
U	Energy stored
V	Volts
V_d	Voltage drop
w	Width
X	Reactance
X_c	Capacitive reactance
X_L	Inductive reactance
Z	Impedance

4. GENERAL REQUIREMENTS

Electrical bonding is the process of providing good electrical connection across mechanical interfaces to minimize electrical potential differences between equipment and individual parts of structure. Good electrical bonding provides fault current paths for protection against fire and personnel shock, provides a current path for radio frequencies for proper operation of filters and shields, provides protection against the effects of lightning, and prevents or safely discharges static charges.

Electrical bonds are classified according to the purpose for the bond. There may be more than one purpose for bonding a specific interface, and the bond shall meet the requirements of each applicable class. Notes shall be provided on assembly drawings indicating the applicable class or classes.

This section describes the various classes of electrical bonding. Each section contains the general requirement, specific design requirements, and, in most cases, measurable resistance values for each class of bond. Notes discuss the reasons for some of the requirements and provide data for possible modifications or rationale for waivers to the requirements.

Table I gives a summary of the classes of bonds.

TABLE I. Summary of Electrical Bonding Classes

	Power Return	Shock Hazard	Radio Frequency	Lightning	Electrostatic Charge
BOND CLASS	**CLASS "C"**	**CLASS "H"**	**CLASS "R"**	**CLASS "L"**	**CLASS "S"**
PURPOSE OF BOND	Reduces power and voltage losses. Applies to equipment & structure, which are required to return intentional current through structure.	Protects against fire or shock to personnel. Applies to equipment & structure that may be required to carry fault current in case of a short to case or structure.	Applies to equipment that could generate, retransmit, or be susceptible to RF. Covers wide frequency range.	Applies to equipment or structure that would carry current resulting from a lightning strike.	Protects against electrostatic discharge. Applies to any item subject to electrostatic charging.
BOND REQT.	Requires low impedance & low voltage across joints to assure adequate power to the user. Jumpers and straps acceptable.	Requires low impedance & low voltage across joints to prevent shock hazard or fire due to short. Jumpers and straps acceptable.	Requires low RF impedance at high frequency. Direct contact preferred. No jumpers. Short, wide strap may be used as last resort.	Requires low impedance at moderate frequency. Bonding components must withstand high current. Straps and jumpers must withstand high magnetic forces.	Allows moderate impedance. Jumpers and straps acceptable.
DC BOND RESISTANCE REQT.	Bonding resistance requirement depends on current.	Bonding resistance requirement, 0.1 ohm or less. Special requirements when near flammable vapors.	Bonding resistance requirement, 5.0 milliohms or less. Low inductance required.	Bonding resistance requirement depends on current. Low inductance required.	Typical bonding resistance requirement, 1.0 ohm or less.
FREQ. REQT.	Low	Low	High	High	Low
CURRENT REQT.	High	High	Low	High	Low
	Low frequency bonds allow use of straps and jumpers. High frequency bonds require low inductance paths. Short straps sometimes acceptable. High current bonds require large cross sectional areas. Low current bonds allow use of small contact areas.				

4.1 Power Current Return Path (Class C). Small satellite systems are occasionally designed to allow dc power to be returned through structure. When this is the case, the total voltage drop across all joints between the power supply and the load shall be controlled in order to keep the voltage within the tolerance of the applicable power quality standard. If no power quality standard is applicable, a default voltage drop value of 3.5% shall be used (one volt drop for 28-volt systems and four volts for 120-volt systems). The voltage drop allowed divided by the maximum current that may be delivered by the power supply will give the total resistance allowed in the circuit. This resistance includes the wire, its connectors, and all bonded joints in the structure return path. The resistance limit for each joint can then be allocated.

Structure with joints located in oxygen enriched areas or where flammable vapors may occur shall not be used as the primary current return path. A primary current return path shall be provided around the hazardous area to prevent arcs or hot spots. The resistance limits of Figure 1 are applicable to class "C" bonds in flammable atmospheres as well as for fault current.

Magnesium alloy structure shall not be used as an intentional current return path. The temperature of a poor joint could rise to the ignition point of magnesium.

A dedicated return is preferred over the use of structure for power current return and will be stated as a requirement for most programs.

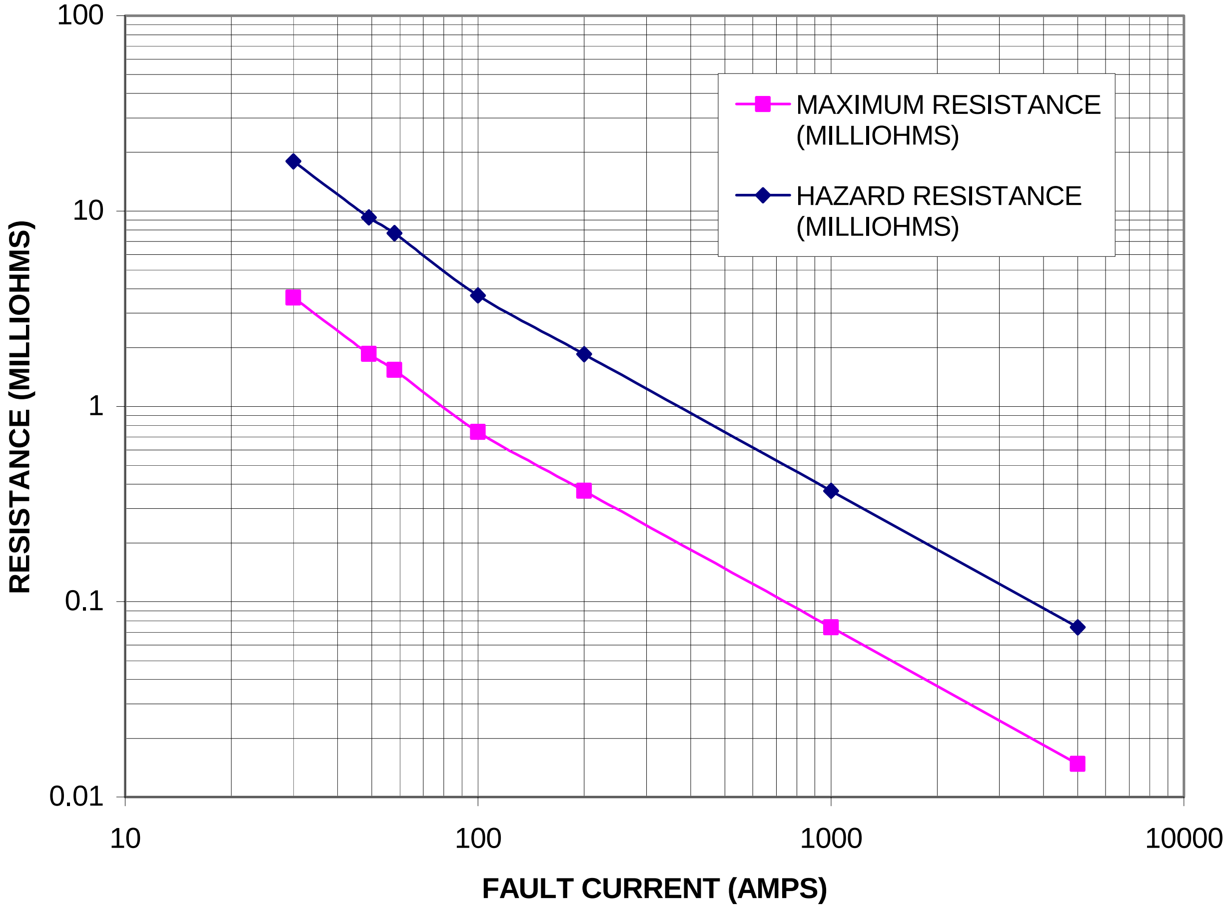
Refer to paragraph 6.2 for more information.

4.2 Shock and Fault Protection (Class H). Fault current, due to short circuits to equipment case or structure, may cause shock or fire hazards. All electrically conductive equipment cases that may develop potentials due to short circuits shall be electrically bonded to structure. The bond shall minimize shock hazard voltages and allow proper operation of circuit protection devices such as circuit breakers or fuses. Bonding of structural joints in the fault current return path shall provide for the maximum current that may be delivered by the power supply until the fuse or circuit breaker disconnects. For personnel and fire safety the fault current return path shall be capable of conducting a minimum of 5 times the breaker "must break" rated current for a time period long enough to trip the breaker. Typical personnel protection breakers will trip within 0.2 seconds after a hard short to case.

Exposed cases or chassis of electrical or electronic equipment shall be bonded to structure with a resistance of 0.1 ohm or less. Metallic conduit, cable trays, and other conductive objects susceptible to short circuits shall have a resistance to structure of 0.1 ohm or less.

Electrical bonding of mating surfaces in areas where explosive fuel or gas may be present shall be adequate to prevent ignition due to heating or arcing. Resistance across each of these joints shall not exceed the maximum resistance values shown in Figure1. There is a 14-dB margin between the actual hazard resistance and the maximum resistance allowed.

Refer to paragraph 6.3 for more information.



FAULT CURRENT (AMPS)	MAXIMUM RESISTANCE (MILLIOHMS)	HAZARD RESISTANCE (MILLIOHMS)
30	3.6	18
49	1.86	9.3
58	1.54	7.7
100	0.74	3.7
200	0.37	1.85
1000	0.074	0.37
5000	0.0148	0.074

FIGURE 1. Fault Current vs. Maximum Allowed Bonding Resistance in the Presence of Flammable Vapors or Liquids

(Based on data from MIL-B-5087B)

4.3 Electromagnetic Interference or Radio Frequency (Class R). Basic structure and vehicle skin shall be designed and constructed to provide a uniform low-impedance path at radio frequencies so that system operational requirements are met. RF bonding is required between all conductive basic structural components of the vehicle.

All electrical and electronic equipment shall be installed to provide a continuous low impedance path from the equipment enclosure to the structure. The bond from the equipment enclosure to any mounting plate furnished with the equipment also shall comply with these requirements.

Electrical connectors and their backshells that may be used to terminate cable shields shall be installed to provide a low impedance path from the backshell to the equipment case.

The path to structure and the joints in that path shall be designed such that the inductance and overall impedance including resonances are low enough to prevent interference at the frequencies of interest. The dc resistance across each joint in the path shall not exceed 5 milliohms. Paragraph 6.4 contains information that should be helpful for impedance calculations.

Direct contact between mating surfaces is the preferred method for electrical bonding. Bonding straps may be the only alternative where equipment is vibration or thermally isolated. If straps are used, they shall be flat and have a length-to-width ratio of less than 5 to 1 to minimize the inductance of the strap.

Straps shall not be used for bonding transmitters and receivers.

4.4 Lightning Protection (Class L). Protection against lightning strikes must be provided for launch vehicles and their payloads during transportation, storage, prelaunch, launch, and landing. Propellant, pyrotechnics, and electronic equipment are particularly susceptible to direct and indirect effects of lightning. There shall be a designed path for lightning current from attach point(s) to exit point(s). The design path shall provide the lowest impedance path for lightning current between attach and exit points. The goal is to direct the lightning current away from critical areas (pyrotechnic devices, rocket motors, fuel, flush mounted antennae, electronic equipment, and cables.)

Multiple rivets, bolts, or other fasteners shall be used at joints in vehicle skin and structure to share lightning current. Doors, hatches, and other apertures shall be bonded with multiple connections to minimize aperture size and slot length. Minimizing aperture size reduces induced currents in underlying cables.

Fuel and pyrotechnics shall be completely enclosed by a Faraday cage of conductive material bonded to structure. Wires to pyrotechnics shall be shielded and the shields shall have 360° terminations to the metal enclosure.

The lightning current waveforms defined in SAE ARP 5412 shall be used for analysis to determine design requirements of the bond.

Each electrical bond shall have low resistance and adequate contact area to carry its share of lightning current without burning, melting, or other heating effects from the long-duration, high-current portion of the lightning strike. The bonds shall have low inductance to prevent arcing and coupling of voltage spikes into electronic circuits due to the fast rise time portion of the lightning strike.

The conductivity requirement of the bond will depend upon the current to be carried and the number of parallel paths. The inductance of the bonded joint can not usually be verified in the final configuration, but the inductance shall be kept low enough to prevent damage from induced current and magnetic forces.

If bond straps must be used, they shall be as short as possible. They shall have adequate lug contact area and adequate wire/lug cross sectional area to carry the lightning current. Their cross sectional area shall not be less than that of two AWG 12 wires (6530 circular mils) for stranded copper, and not less than two AWG 10 wires (10,380 circular mils) for aluminum. They shall be robust enough to withstand magnetic forces caused by the high current through the strap, and they shall not rely on soldered connections to carry lightning current. For multistroke protection or if arcing at the jumper is expected the total cross sectional area of the straps should be 40,000 circular mils or greater.

Refer to paragraph 6.5 for more information.

4.5 Electrostatic Discharge (Class S). Electrostatic charges may be caused by precipitation static effects, tribocharging, fluid flow, air flow, space and launch vehicle charging, separation of elements, and other charge generating mechanisms. Electrostatic charges shall be controlled and dissipated to avoid fuel ignition and ordnance hazards, to protect personnel from shock hazards, and to prevent performance degradation or damage to electronics.

Flight vehicles shall be designed to have a resistance of one ohm or less between all parts of conductive basic structure for control of electrostatic discharge.

All conducting items, except antennas, having any linear dimension greater than three inches, which are subject to frictional or other charging mechanisms, shall have a mechanically secure electrical connection to the vehicle structure. The resistance across the connection shall be one ohm or less. Since no high frequencies are involved, jumpers and straps may be used as necessary for class “S” bonds.

All metallic layers of insulation blankets shall be bonded together. The conductive attach points shall be bonded directly to structure, or straps may be used from the attach points to structure. Two attach points to structure per blanket shall be used for redundancy. Resistance from attach points to structure shall be one ohm or less.

Small components located in hazardous fuel areas that are capable of delivering more than 0.25 millijoules through a static discharge shall be bonded with one ohm or less resistance to structure.

All metallic pipes, tubes, and hoses that carry fluids shall have a mechanically secure connection to the structure that will measure one ohm or less. The pipe, tube, or hose installation shall be designed so that it will not be a primary path for electrical power under normal or fault conditions.

In the paragraphs above, a limit of one ohm is used as a requirement because it is easily obtained with good contact between conductive surfaces. Static charges can usually be dissipated through less conductive connections. Waivers to the one-ohm requirement may be allowed for special situations.

Nonmetallic plumbing installations shall be designed so that the static voltage generated by fluid flow will not exceed 350 volts at any point outside the pipes, tubes, or hoses. The resistivity of nonmetallic hoses shall not exceed one megohm per meter to dissipate charges developing within the fluid or between fluid and the hose.

In borderline cases, to determine whether an item requires bonding for electrostatic discharge, calculate the amount of energy that can be stored on the item. Compare it to the applicable hazard threshold levels for shock, equipment upset, and fuel or electro-explosive device (EED) ignition. Determine the required resistance to ground to limit the energy or discharge time to acceptable levels. Calculation methods are described in paragraph 6.6.

5. DETAILED REQUIREMENTS

5.1 Bonding Methods. Equipment and structure with metal-to-metal joints that are joined by processes that transform the mated surfaces into one piece of metal, such as by welding or brazing, are considered permanent and inherently bonded. Semipermanent joints are held together by screws, rivets, clamps, etc. Semipermanent mating surfaces shall be cleaned of all insulating material before connection to provide a good electrical bond. Clamping pressure across the joint shall be adequate to assure a secure mechanical connection. Fasteners or their threads shall not be used as primary bonding paths. A good dc connection will not exceed the 5–milliohm limit for class “R” bonds.

Bond straps or jumpers may be used to meet class “C”, “H”, or “S” bonding requirements. Bond straps or jumpers are useful in some cases for class “L”, but their usefulness for class “R” bonds is very limited. Straps for class “R” bonds shall be used only as a last resort.

Special requirements may be necessary for tubing, composite materials, metalized thermal blankets, etc. Some of these special requirements are discussed in paragraph 6.9.

5.2 Surface Cleaning and Finishing. The mating surfaces of all electrically bonded metal-to-metal joints shall be cleaned of all nonconductive materials and protected against corrosion. Aluminum mating surfaces shall be cleaned of aluminum oxide and other nonconductive materials. The bare aluminum shall be treated with a chemical conversion coating in accordance with MIL-C-5541E, Military Specification, Chemical Conversion Coatings on Aluminum and Aluminum Alloys. MIL-C-5541E describes the cleaning procedures for aluminum surfaces and the process of applying chemical coatings by spray, brush, or immersion. Use class 3 coating for lower resistance.

Magnesium alloys, when allowed, shall be cleaned and treated in accordance with MIL-M-3171C, Magnesium Alloys, Processes for Pretreatment and Prevention of Corrosion. The type I, chrome pickle, treatment shall be used.

Treated mating surfaces shall be protected by packaging materials or protective films until just prior to mating. After protective material is removed, the surfaces shall be cleaned by blowing, vacuuming, or wiping with appropriate solvent as necessary to remove dust or other foreign particles before mating.

Steel may be painted as required for corrosion protection except at faying surfaces. Paint or other nonconductive finishes shall be removed from faying surfaces where electrical bonding is required. Nonhardening sealant may be used between removable equipment and steel structure. Hardening sealant may be used on faying surfaces of permanent installations if mounting is done before the sealant hardens. Tests shall be performed using sealant on

samples to determine proper working time and mounting procedures. Tests shall assure surfaces to be bonded will meet bonding requirements using either type of sealant.
Other methods of protecting conductive mating surfaces include coating the materials with noncorrosive metals such as nickel.

Surfaces that are expected to remain mated indefinitely shall be inspected periodically to maintain a good bond.

5.3 Galvanic Corrosion of Dissimilar Metals. The galvanic series gives a voltage level for each material immersed in an electrolyte solution. The voltages may differ with the electrolyte, and the order of the material in the series may even change. The galvanic series using seawater as an electrolyte is used for most aerospace work. Table II is an example. Metals in the same group in the table may be placed in contact with each other.

Where dissimilar metals are placed in contact, galvanic reaction may cause corrosion of the metal that is higher (more anodic) in the galvanic series. Corrosion impedes current flow and damages metal. An intermediate metal, placed between two metals that are far apart in the series, will reduce the tendency to corrode.

If the mating of dissimilar metals cannot be avoided, the most active of the metals should be replaceable in reusable vehicles. In all applications the electrolyte contact area of the most anodic metal, higher in the series, shall be larger than that of the cathodic metal. The larger the anodic area the lower the current density on the anode. Small parts, such as fasteners, shall be made of material compatible with the more cathodic metal. An approved sealant shall be used to seal all edges from moisture.

TABLE II. Galvanic Series*

More Active (Anodic)	
Group I	magnesium
Group II	zinc aluminum aluminum alloy 7072 aluminum alloy 7079-T6 cadmium aluminum alloy 6061-T6 aluminum alloy 2024-T4
Group III	tin stainless steel 430 (active) lead steel 1010 cast iron
Group IV	nickel chromium stainless steel 430 (passive) brass
Group V	copper Monel 400 titanium silver gold graphite
Less Active (Cathodic)	

* Data Taken From MIL-STD-8898 and AFSC DH 1-4

5.4 Special Considerations. Some materials are poor conductors and some configurations are not readily bonded. In those cases, we may have to settle for less than perfect bonding and note the limitations of the bond. The bond may still be satisfactory for controlling static discharge in many cases, but it cannot be used for fault current return or good RF bond. Some of these special cases are discussed below.

Tubing and hoses that carry fluids shall have a connection to structure of one ohm or less. Nonmetallic plumbing installations shall be designed so that the static voltage, generated by fluid flow, will not exceed 350 volts at any point outside the pipes, tubes, or hoses. To control ESD within the fluid or the tubing, the tubing material shall have a resistivity less than one megohm per meter of length.

Graphite filament reinforced plastic (GFRP) provides some conductivity through the graphite filaments. However, the graphite is usually covered with nonconductive epoxy or phenolic material. GFRP shall be bonded to control ESD and may be useful as a RF bond, but it shall not be the primary path for intentional power or fault current return. The procedure for bonding GFRP requires removing enough nonconductive material from the mating surfaces to expose the graphite layer. Electrical bonds between GFRP sheets can be made by overlapping exposed graphite on both sheets. Conductive epoxy may also be placed on the exposed graphite, and bonding connections may be made to metallic surfaces through the conductive epoxy.

Multilayer insulation is usually composed of several layers of plastic material with conductive metal coating on one or both sides of each layer. The conductive surfaces of all layers shall be bonded together and provisions shall be made for attaching to structure, directly or through bond straps. The resistance from the conductive surface to the structure or bond strap shall not exceed 1000 ohms.

5.5 Verification. Verification of electrical bonding requirements shall be accomplished by a combination of tests, similarity, analysis, and inspection. The resistance of bonds may be measured on flight vehicles, but it is usually impractical to measure inductance or current carrying capability.

The resistance requirement of all classes of bonds shall be verified by testing sample bonds. Other bonds of the same type, using the same procedures, may be verified by similarity. Spot checks shall be made to verify the process is still good and is being followed.

Class “C”, “H”, and “L” bonds require current carrying capability, as well as, low resistance contacts. The current carrying capability shall be verified by analysis and inspection.

Class “R” and class “L” bonds require low inductance paths as well as low resistance. The low inductance path shall be verified by analysis and inspection.

6. NOTES

6.1 Design Requirements. This standard uses the familiar classification system used by MIL-B-5087B that has been superseded by MIL-STD-464. Electrical bonding is performed in accordance with the requirements of the strictest applicable class. In many cases the most strict requirement must be chosen from more than one class, since each applicable class may have a requirement that is more strict than the other classes.

An example of electrical bonding for more than one purpose would be a piece of electronic equipment powered from the system power supply. It would require class “R” bonding for radio frequency and class “H” bonding for fault current protection. Since both classes are applicable, the bond must be low inductance with no more than 5 milliohms dc resistance for class “R”, and the contact area must be adequate to carry the maximum fault current that could occur for class“H”.

A nose cone should meet the lightning and static charge requirements. The class “L” requirement calls for low inductance, low resistance, and adequate area to carry lightning current. Since the bond requirement for static charge is only moderately low resistance the lightning bond will be sufficient for both.

The only requirement for conductive tubing carrying fluid will be to meet the class “S” requirement. An electrical bond to basic structure of one ohm or less will be adequate.

6.2 Power Current Return Path (Class C). A dedicated power return is preferred over the use of structure for power current return and will be stated as a requirement for most programs. However, structure return is occasionally used for some systems such as small satellites.

In those cases where structure current is used, the total resistance allowed for the power distribution system may be determined by dividing the allowable voltage drop (V_d) by the maximum current $(I_{\max})$ that can be delivered by the power supply.

$$R_t = \frac{V_d}{I_{\max}} \tag{6.1}$$

The resistance includes that of the wire, the connectors, the structural material, and all bonded joints in the return path. Maximum resistance limits for each individual joint can then be determined by dividing the resistance allocated for all bonded joints in the worst return path by the number of joints in the path. This should result in a conservative margin since most joints will be less than the maximum allowed.

6.3 Shock and Fault Protection (Class H). The fault current, resulting from a short between a power wire and a metallic equipment case or other conductive structure, must return through structure and the joints in the structure to its source. Circuit protection devices are intended to limit the duration of fault current events to prevent a significant temperature increase in the circuit wiring. Typically, the fault current is considerably higher than the fuse or breaker value, and it trips the device quickly. However, a circuit breaker can sometimes take several seconds to trip with a current twice its rating. Resistance across all the joints in the return path must be low enough to allow enough current to trip circuit protection devices in a timely manner.

SAE ARP 1870, Aerospace Systems Electrical Bonding and Grounding for Electromagnetic Compatibility and Safety, restricts voltages on electronic equipment cases to less than 4.5 volts and requires no fire or damage to the bond in the event of a short to case.

For shock protection from voltages exceeding 30 volts the break time should not exceed 0.2 seconds.

Structural material that is not highly conductive, such as graphite filament reinforced plastic, may increase the path resistance enough to delay or prevent tripping the circuit breaker. In addition to being a shock hazard, fault current can cause ignition of graphite epoxy material. Straps or jumpers may be adequate for fault current returns, but low resistances are required. The inductance of the strap is not a concern since the high current will be from a dc or low frequency ac power source.

6.4 Electromagnetic Interference or Radio Frequency (Class R). The class "R" bond is not required on all equipment, but it is difficult to determine in advance which equipment really needs to be well bonded. The low impedance to structure is necessary for certain power line to equipment filters and for proper operation of cable shields terminated to equipment chassis. Isolated structural elements with linear dimensions approaching $\lambda/2$, where λ is the wavelength, can pick up RF from high power transmitters and develop enough voltage to produce a glow discharge or arcing to other elements.

There is no RF design basis for the historical 2.5-milliohm requirement except to ensure a good metal-to-metal contact that can be expected to be consistent. This limit sometimes cannot be met when mating two aluminum surfaces that have had a chemical conversion coating such as Iridite 14-2 to prevent corrosion. Well-bonded joints with treated surfaces can meet the 5–milliohm requirement.

The basic requirement is to have low impedance at the frequency or frequencies of interest. The value of this impedance, which is not defined, depends upon the situation. The impedance of an acceptable bond may be in the ohms range for RF even though the dc resistance is less than 5 milliohms. The resistance is overshadowed by the inductive reactance of the configuration.

Any electronic equipment with conductive mounting feet will probably have an inductive reactance greater than 5 milliohms at frequencies above 10 MHz. RF bonds may be satisfactory with several ohms of impedance; but, when straps are used, even these levels will be quickly exceeded as frequency increases. Some procedures limit bond strap length to width ratios to 3 to 1 or 5 to 1. The impedance of these straps exceeds 2.5 milliohms at approximately 20 kHz. The impedance of a strap with length to width ratio of 5 to 1 is at least 100 milliohms at 1 MHz and 1 ohm at 10 MHz.

The 5-milliohm, dc resistance requirement is good for a standard, but extra effort need not be made just to satisfy the dc requirement if the RF impedance is much higher due to the inductance of the configuration. Look at the whole configuration to get the lowest impedance possible at the frequencies of interest to produce a good RF bond.

The electrical bond path between an electronic box and structure has a complex equivalent circuit that may be simplified to a resistance in series with an inductance all in parallel with a capacitance. The equivalent resistance includes the resistance of any bond strap present plus the resistance of the joints in the path. This resistance is usually low and remains constant with increasing frequency; except, in some configurations, the skin effect may cause a slight increase in resistance at higher frequencies.

The inductance is directly proportional to the length of the bond path. Wider paths and multiple paths can reduce the inductance value. The inductive reactance increases 20 dB with every decade of frequency increase.

The capacitance between the box and structure is proportional to the area of the interface and inversely proportional to the distance between the box and structure. The capacitive reactance decreases 20 dB per decade of frequency increase.

The circuit becomes parallel resonant at a frequency where the inductive reactance and the capacitive reactance are equal. At this point the impedance may reach thousands of ohms depending on the Q of the circuit.

According to Terman's Radio Engineers' Handbook, the inductance (L) of a flat metal strap is given by:

$$L = 0.002\, l \left[\ln\left(\frac{2l}{w+t}\right) + 0.5 + 0.2235\left(\frac{w+t}{l}\right) \right] \mu H \tag{6.2}$$

Where,

L = inductance (microhenries)
l = length (centimeters)
w = width (centimeters)
t = thickness of the strap (centimeters)

The low frequency inductance (L) of a round jumper of nonmagnetic material is given by:

$$L = 0.002\, l \left[\ln\left(\frac{4l}{d}\right) - 0.75 \right] \mu H \tag{6.3}$$

Where,

l = length (centimeters)
d = diameter of the jumper (centimeters)

At higher frequencies the inductance of a round jumper is limited to:

$$L = 0.002\, l \left[\ln\left(\frac{4l}{d}\right) - 1 \right] \mu H \tag{6.4}$$

The inductive reactance (X_L) of the strap or jumper is:

$$X_L = 2\pi f L \text{ ohms} \tag{6.5}$$

Where,

f = frequency (hertz)
L = inductance (henries)

The capacitance (C) between a box and structure is found by:

$$C = 0.08842 \times k\left(\frac{A}{d}\right) \rho F \tag{6.6}$$

Where,

C = capacitance (pF)
k = dielectric constant (k = 1 for air)
A = area of mating surfaces (square centimeters)
d = distance between the box and the structure (centimeters)

The capacitive reactance (X_C) is:

$$X_C = \frac{1}{2\pi f C} \text{ ohms} \tag{6.7}$$

Where,

f = frequency (hertz)
C = capacitance (farads)

The total impedance across the joint is equal to the resistance at frequencies from dc to the point where the inductive reactance approaches the resistance. The impedance due to inductance then increases at 20 dB per decade of frequency to a frequency where the inductive reactance and the capacitive reactance are equal. The capacitive reactance is high at low frequencies, but it decreases as frequency increases. At this resonant frequency the impedance may rise to thousands of ohms depending on the ratio of reactance to resistance (Q) in the circuit.

The Q is high when the resistance is low, which is usually the case for a bonding joint. At frequencies above this point, the capacitive reactance is less than the inductive reactance; and the total impedance begins to come back down. Often there are more complex series and parallel resonances; and, at the higher frequencies, the impedance may vary considerably.

The resonant frequency (f_{res}) is found by:

$$f_{res} = \frac{1}{2\pi\sqrt{LC}} \text{ hertz} \tag{6.8}$$

Where,

f_{res} = resonant frequency (hertz)
L = inductance (henries)
C = capacitance (farads)

The impedance (Z) at resonance is:

$$Z = \frac{X^2}{R} \tag{6.9}$$

Where,

Z = impedance (ohms)
X = inductive or capacitive reactance at the resonant frequency
R = resistance of the circuit (ohms)

Q = ratio of the reactance to the resistance:

$$Q = \frac{X}{R} \tag{6.10}$$

And,

$$Z = QX \tag{6.11}$$

It can be seen that impedance due to strap inductance quickly exceeds the 5-milliohm requirement as frequency increases. When the capacitance between the equipment and its mounting surface is considered, some resonant frequency will be found where impedance is very high. Even though RF bonds may be satisfactory at several ohms of impedance the straps quickly exceed even these levels.

The following examples demonstrate the use of some of the preceding equations and illustrate the importance of considering resonance when bond straps are used.

Assume a round #4/0 wire and a flat strap with the following characteristics:

Round copper wire:	
Cross sectional area (A)	1.072 square centimeters
Diameter (d)	1.168 centimeters
Resistance (20-cm length)	32.2×10^{-6} ohms

Flat copper strap:	
Cross sectional area	1.072 square centimeters
Thickness (t)	0.16 centimeters
Width (w)	6.70 centimeters
Resistance (20-cm length)	32.2×10^{-6} ohms

Use equation 6.3 to calculate the inductance of the round wire:

$$L = 0.002 \times 20 \left[\ln\left(\frac{4 \times 20}{1.168} \right) - 0.75 \right] \mu H$$
$$L = 0.1391\ \mu H$$

Use equation 6.2 to calculate the inductance of the flat strap:

$$L = 0.002 \times 20 \left[\ln\left(\frac{2 \times 20}{6.7 + 0.16} \right) + 0.5 + 0.2235 \left(\frac{6.7 + 0.16}{20} \right) \right] \mu H$$
$$L = 0.0936\ \mu H$$

The impedance of each at 10 MHz is found by equation 6.5.

For the round wire:

$$X_L = 2\pi\left(10\times10^{6}\right)\left(0.1391\times10^{-6}\right)$$
$$X_L = 8.74\ ohms$$

For the flat strap:

$$X_L = 2\pi\left(10\times10^{6}\right)\left(0.0936\times10^{-6}\right)$$
$$X_L = 5.88\ ohms$$

Assume a box has a mounting footprint of 306 square centimeters and is coated with nonconductive paint 0.01 centimeters thick. Equation 6.6 can be used to determine the capacitance between the box and the structure. Assume the paint has a dielectric constant of 1.

$$C = 0.08842\times1\left(\frac{306}{0.01}\right)$$
$$C = 2706\ pF$$

If the flat strap is used to bond this box to structure, the inductance and capacitance are parallel resonant at a frequency determined by equation 6.8.

$$f_{res} = \frac{1}{2\pi\sqrt{0.0936\times10^{-6}\times2706\times10^{-12}}}$$
$$f_{res} = 10\times10^{6}\ Hz = 10\ MHz$$

The Q of the circuit is found by equation 6.10:

$$Q = \frac{5.88}{32.2\times10^{-6}}$$
$$Q = 1.8\times10^{5}$$

The impedance at 10 MHz is found by equation 6.11:

$$Z = 1.8\times10^{5}\times5.88$$
$$Z = 1.058\times10^{6}\ ohms$$

6.5 Lightning Protection (Class L). Electrical bonding in itself does not ensure lightning protection, but it is a major part of the overall plan. Lightning current usually enters one extremity of the vehicle and exits at another extremity. Lightning current is high and voltages developed across joints are high enough to arc and provide a path to some exit point. A good current path should be provided around the outside of the vehicle to help protect internal equipment. Electrical bonding helps provide the proper continuity for the path.

Even when a large current path is provided to carry the current, attach points across joints still may present a problem. Arcing at joints can be expected even with good electrical bonds. Lightning current waveforms, as defined in SAE ARP 5412, have rates of rise of 1 X 10^{11} amps/second. Considering a bond connection with inductance of 0.1 μH would result in a voltage spike across the joint of 10,000 volts. The arc produces an ionized path that helps carry the current. The majority of the current can be kept external to the vehicle through good electrical bonding of the vehicle skin.

When bonding straps are used, they should be kept short to ensure that inductance and resistance are kept as low as possible. The strap and connections should be robust enough to survive the high lightning current and the magnetic forces resulting from high lightning current. Straps should not have loops or bends greater than 45° to avoid damage from magnetic forces. Information concerning lightning bonds may be found in “Lightning Protection of Aircraft” by Lightning Technologies, Inc.

Apertures should be kept as small as possible. Joints should be bonded in many places to prevent long slots between bonds. Joints and apertures in the skin allow some voltage to be induced into underlying cables. This voltage must be kept low enough to prevent disrupting electronic equipment.

Special care must be taken to route current around fuel or pyrotechnics to prevent arcs that can ignite fuel or current that can fire pyrotechnics. Fuel and pyrotechnics should be completely enclosed by a Faraday cage of conductive material bonded to structure to provide an adequate margin against ignition. Wires to pyrotechnics should be shielded and the shields should have 360° terminations to the metal enclosure.

6.6 Electrostatic Discharge (Class S). The resistance to ground, structure, or another lower charged object affects the rate of discharge for an item being charged. A low resistance reduces the charge faster, but bonds with resistances that would be considered high, such as 10 kilohms to 100 kilohms, usually function adequately. The charging current, usually in microamps, returning through the resistance to ground determines the voltage developed.

A requirement for one ohm or less to ground is a good requirement for metal items because any good metal-to-metal connection will measure less than one ohm. Under some circumstances, such as when semiconductive materials or complex configurations are used, this limit may be increased up to ten kilohms. Metal straps or jumpers across joints are adequate since the current is dc.

An arc discharge can cause direct effects to the item being discharged and to the item receiving the discharge. Indirect effects may be caused by voltages induced into neighboring items. Direct or indirect effects include physical damage to an item, upset of operation, ignition, or shock to personnel.

In summary, bonding for electrostatic charge should use the one-ohm requirement for ordinary metal joints to ensure a good connection. The one-ohm requirement simply ensures the metal-to-metal bond is a clean, quality bond that will retain its conductivity. Good connections that measure up to 10 kilohms from equipment to ground for unusual configurations or semiconductive materials may be acceptable. Jumpers and straps may be used.

6.7 Surface Cleaning and Finishing. MIL-C-5541 describes the cleaning procedures for aluminum surfaces and the process of applying chemical coatings by spray, brush, or immersion.

This standard provides for class 1A coatings for maximum protection and class 3 where electrical conductivity is required. Class 3 may use a different material, or it may be a thinner coating using the same material as for class 1A. The coating materials are required to meet MIL-C-81706, Chemical Conversion Materials for Coating Aluminum and Aluminum Alloys. Commonly used examples of these materials are Iridite 14-2, Alodine 600, and Alodine 1200. The more conductive class 3 coating uses a short immersion time or is brushed on to form a thinner coating.

The thinner coating is more conductive, but the thicker coating is still more conductive than the aluminum oxide on the original material. To meet the 5-milliohm resistance limit, a thin coating may be required. However, even the thicker coatings usually measure less than 10 milliohms.

The type 1, chrome pickle, treatment of MIL-M-3171C is used for magnesium alloys. This process uses a weak chromic acid solution to clean down to bare metal. The coating process uses sodium dichromate and nitric acid that etches some of the surface away and deposits a chromate coating.

MIL-B-5087B prohibited the use of cadmium plated steel for space applications. Cadmium sublimates and may deposit on optics, solar arrays, etc. MIL-B-5087B also prohibited the use of zinc plating. It did not allow the use of magnesium as a current return path. Magnesium is flammable if the temperature is high enough. STP 6511J does not allow tin-coated hardware near liquid or gaseous oxygen, because tin oxidizes easily.

The use or non-use of these or other materials is not specified by this standard, and they are mentioned here as a reminder to check materials usage requirements before use.

6.8 Galvanic Corrosion of Dissimilar Metals. It is recommended to follow the guidelines in MIL-STD-889B, Dissimilar Metals. This standard contains considerably more information on the subject, and includes expanded lists of compatible and incompatible materials.

6.9 Special Considerations. The movement of fluid through a hose or tubing provides a charging source. If the fluid is not conductive, it can carry charges to conductive items in the fluid path. Conductive items in the fluid flow path must be bonded to structure to prevent a static charge buildup.

Conductive hose or tubing grounded to structure will help prevent charging. Conductive fluids can also prevent the charge separation. With a nonconductive fluid in nonconductive tubing, the charge may transfer to conductive items in the line or, if enough potential develops, a discharge may occur through an arc from the fluid through the tubing to a metal sheath or other conductive items outside the tubing. This arc may produce small holes in the tubing.

Tubing is available that is somewhat conductive and prevents the separation and movement of the charge if its resistivity is less than one megohm per meter of length. Fluids with volume resistivity less than 10^7 ohm-meters are conductive enough to prevent the separation of charge, but there is seldom a choice of fluids.

Some composite materials are nonconductive and should not be used where static discharge could be a problem. Graphite filament reinforced plastic (GFRP) or composite materials that contain metal particles are usually conductive enough to drain off static charges if given a conductive path from the material to metallic structure.

Since these composite materials are relatively poor conductors, they should not be used to carry high current. The resistance would cause excessive voltage drop for intentional power return, and short circuit current may be limited to levels too low to trigger circuit protection devices.

GFRP may be used as RF ground even though its dc resistance may exceed the usual class "R" limits. If the resistance through the composite structure can be kept to a few ohms, the total impedance to RF will depend upon the inductance of the configuration just as it would with metal.

Special attention must be given to bonding across joints in composite materials. The graphite layers are conductive, but epoxy or phenolic may cover the outside layers of the composite. This nonconductive outer layer must be removed to expose the graphite so conductive connections may be made at joints. If the bond is for RF purposes, do not depend on narrow straps. The connection should be continuous along edges that have been abraded to expose graphite. Connection may be made by overlapping panels or by adding a conductive bridge secured by metal fasteners or by conductive adhesive across the joint.

The conductive layers of multilayer insulation may be bonded together at several points using accordion shaped metal foil fitted into the edges of the conductive layers so that each conductive layer contacts the foil. A rivet or bolt through the layers and the foil will assure contact and will provide a point for attachment to structure. Good conductivity should be verified by test.

6.10. Verification. Testing of every joint in a vehicle is neither required nor desirable. Usually tests of certain processes can verify that the process will result in a satisfactory bond. Other bonds using the same process can be verified by similarity. Verification that the same process was used on each bond should be adequate.

There are requirements in addition to dc resistance measurements that depend upon the class of bond required. For class "C", "H", and "L", the bond must have enough contact area to carry the intentional, fault, or lightning current. Class "L" bonds must also be robust enough to withstand the magnetic effects of the large current being carried if they are to be useful for more than one strike. These requirements are typically verified by analysis and inspection of the drawings and the installation.

Class "R" bonds should be low impedance at the frequency of interest. Calculations should be made to determine the impedance of any RF bond other than direct metal-to-metal contact over a large surface area. In short, bonding should be verified by analysis, some tests of actual bonds, tests of samples of a process, inspection of physical bonds and processes, and similarity to other good bonds.